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Unusual river turbidity and water quality hysteresis in the most urbanised catchment in the UK

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Abstract: Over 50% of the world's population is now urbanised, and this proportion will rise to 60% by 2020. It is vital, therefore, that we develop understanding of how urban processes and related hydrological changes impact on water resources, water quality and water pollution dynamics. However, little is known of the dynamics of storm-event sediment and pollutant transport in urban rivers. In many catchments, it is often assumed that polluting fine sediment fluxes are delivered early in the storm, peaking before the flow maximum, i.e. the 'First-Flush' Model (FFM). This paper tests the validity of this First-Flush Model in the most urbanised catchment in the UK: the River Tame, Birmingham, which is 42% urbanised. The paper presents high-resolution hysteresis analyses of key turbidity and water quality datasets, using very high frequency 15-minute data. Determinands include storm-event river flow, rainfall intensity, turbidity, electrical conductivity and Ammonia. Crucially, in 90% of storm events, turbidity peaks occurred, unusually, after river flow peaks. This generated anticlockwise hysteresis - contrary to classic 'First-Flush' model predictions. Of 10 explanatory hypotheses tested, three are of special interest, including (a) the impact of Combined Sewer Overflow ingress, (b) delayed bed sediment destabilization effects (with a new BASS model - Biofilm Adhesion of Sediment Supplies); (c) road-derived particulates generated by some of the heaviest traffic loads in Europe. This unusual storm behaviour suggests that urban impacts on water resources are much more significant and complex than thought, as discussed in a 'Senile Cities' model.

Key words: 'First Flush' model; turbidity; suspended sediment; hysteresis; urban river

1. INTRODUCTION

Sediment inputs and dynamics in rural basins are well understood. However, significant research gaps remain for urban catchments, and rates of global urbanisation are increasing. Research is essential because fine sediment river pollution and water turbidity issues are increasingly problematic, including in estuaries (e.g. Chon et al., 2012; Jonas and Millward, 2010; Murdoch et al., 2010). Key issues include: light penetration problems in the water column, sediment-associated contaminant transport, habitat impacts (Lawler and Wilkes, 2015; Conroy et al., 2016), biological oxygen demand (BOD) implications and water abstraction and treatment problems. Many of these problems increase as urbanization progresses.

Therefore, an improved understanding of sediment pollution dynamics in heavily modified urban systems is needed to improve modelling and management of sediment issues. But this is a challenge, partly because sediment sources and delivery routes and can be modified hydrologically, geomorphologically and anthropogenically (including by direct engineering).

The pioneering work from the 1970s to 1990s by D.E. Walling on fluvial fine sediment transport rates and their differences between seasons, and between rising and falling hydrograph limbs, for a given flow during storm-events (e.g. Walling, 1977; 2008). Such work has been associated with the First Flush Model (FFM) to explain the dynamics of storm-event fluvial suspended sediment concentrations and loads. The First-Flush Model predicts that in-channel suspended sediment concentrations (SSC) will rise sharply early in a storm event and peak *earlier* than maximum discharge. Sediment concentrations will then fall rapidly, as sediment sources become exhausted, even as discharge continues to increase. This generates a positive, clockwise hysteresis loop when discharge is plotted against suspended sediment concentration or turbidity.

However, although the FFM has been shown to apply to a large range of basins, its applicability has been questioned for some urbanised catchments. For example, Lawler *et al.* (2006a,b) and Lawler and Wilkes (2015) found that turbidity levels in many storm events were *higher* for a given discharge on the *falling* limb, which generated an anticlockwise, rather than a clockwise, hysteretic response. This is inconsistent with the FFM.

2. OBJECTIVES

The research reported here builds on these urban river analyses, in which the appropriateness of the First Flush model in the highly urbanised catchment of the River Tame, Birmingham, UK (42% urbanised) is tested for an important spring storm period. High resolution, multivariate water quality datasets at 15-minute time-step are used to define turbidity hysteresis dynamics during a typical storm event.

3. STUDY AREA

The River Tame basin is the most urbanised catchment in the UK (~42% urban). It is located in central England, in the West Midlands region of the country (Fig. 1). The river system drains part of industrial Wolverhampton, Walsall and Birmingham, before flowing into the River Trent, which then discharges into the North Sea via the Humber Estuary (Fig. 1).

The upper catchment has been heavily impacted by disused mine shafts, industrial workings, motorway and highway drainage, contaminated land and waste water treatment works (WWTWs). The catchment contains two monitoring stations, operated by the UK Environment Agency (EA). The main focus here is the James Bridge upstream station with latitude and longitude of 52° 34' 40.5" North and 02° 00' 58.9" West. The Water Orton monitoring station lies approximately 28 km river distance downstream of James Bridge station (Fig. 1).

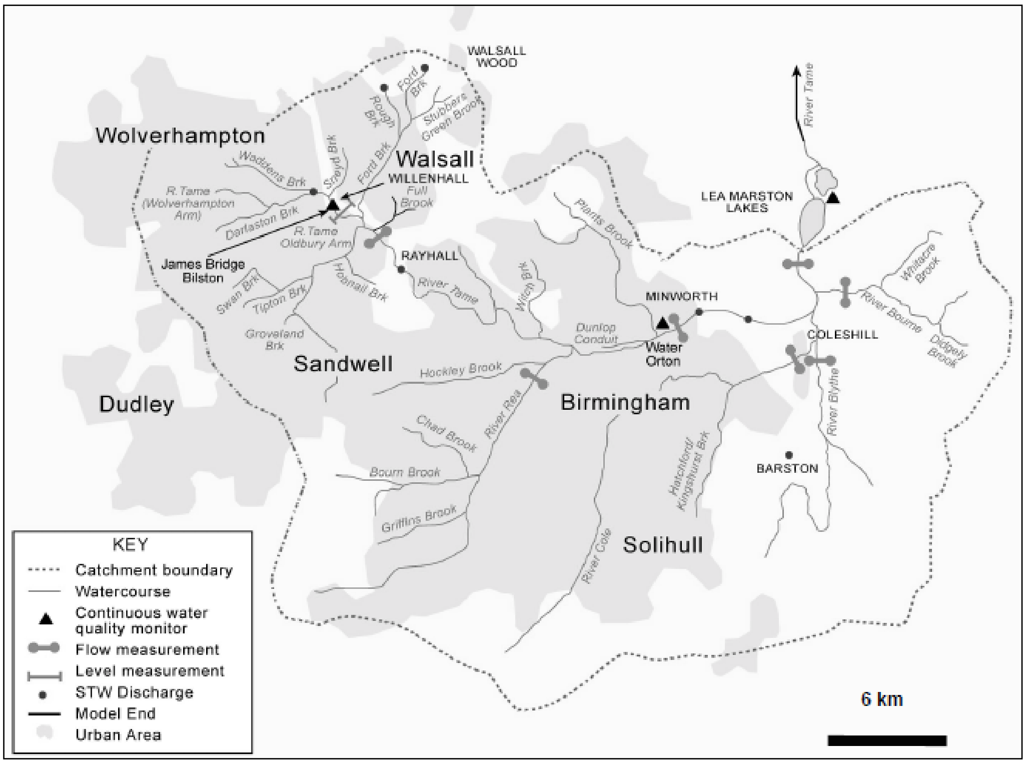

Figure 1. The Tame catchment, Birmingham, central UK, with monitoring stations at James Bridge in Bilston, Walsall (upstream), and at Water Orton (downstream).

4. METHODS

The automatic gauging and water quality monitoring station at James Bridge (Fig. 1) generated 15-minute data on river flow, turbidity, electrical conductivity (EC), water temperature, pH, dissolved oxygen (DO) and ammonia ($NH_3(N)$) (see Lawler et al., 2006a for further details). River water samples were also pumped up automatically from a near-bank intake to a measurement facility housing the detectors for some events. The instrumentation system was cleaned at weekly intervals. Turbidity was monitored in-line with a pHOX 750M absorptiometric turbidity head (Lawler, 2016). Turbidity was measured using a red LED, and optics were automatically wiped clean five times per hour. Monthly end-point calibrations were performed with deionized water and a liquid turbidity standard of 500 FTU (Formazin Turbidity Units; Lawler, 2016). Good correlations were obtained between turbidity and suspended sediment concentrations. Catchment precipitation data at 15-min resolution were available from Willenhall rainfall station (Fig. 1), upstream of James Bridge (Lawler and Wilkes, 2015).

5. RESULTS

An early example of a storm event is shown in Figure 2.

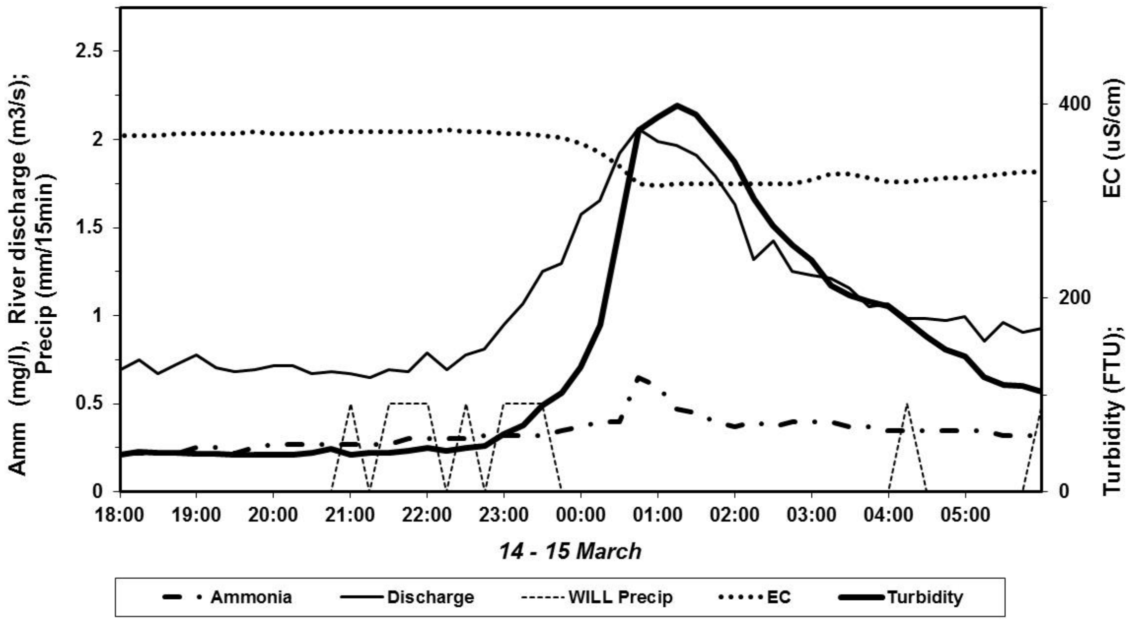

Figure 2. An early example of turbidity peaks following the flow peak for the River Tame at James Bridge, Birmingham, UK. Water quality time series are also shown for this 14-15 March 2002 rainstorm event. 'WILL Precip' is 15-minute frequency precipitation data for Willenhall, in northwest Birmingham. EC is Electrical Conductivity of river water in $\mu S\ cm^{-1}$.

Figure 2 shows a dynamic response of urban river flow to precipitation recorded at Willenhall (Fig. 1). River flow rates begin to rise within 90 minutes of rainfall falling, and the flow rate peaks 4.5 hours after rainfall onset.

Importantly, Figure 2 shows that fine sediment transport response is contrary to normal First-Flush Model (FFM) assumptions. First-Flush Models predict, for a given flow, greater sediment transport on the rising limb of the flow hydrography compared to the falling limb (e.g. Gellis and Walling; Walling, 2008; Lawler et al., 2017). A number of causes have been hypothesised worldwide. One oft-cited driver is the greater sediment availability from pre-weathered exposed soil surfaces and weakened river banks, sediment which become available for erosion and routing to river channels early in a storm (e.g. Walling, 2008). Once this readily-available supply of loosened sediment has been eroded, however, suspended sediment concentrations decline, relative to river discharge.

However, in the River Tame here, the opposite is the case. Most turbid waters come through *after* the discharge peak in the Tame, rather than *before* the flow maximum. Lawler (2006a,b) named these turbid flushes which come through late in the hydrograph as 'Falling-LImb Turbidity Extensions' (FLITEs), as they occur on the recessional limb of the hydrograph. These features also partly relate to limited natural soil and sediment surfaces in urban areas to produce particulate material available for transport to the river channel.

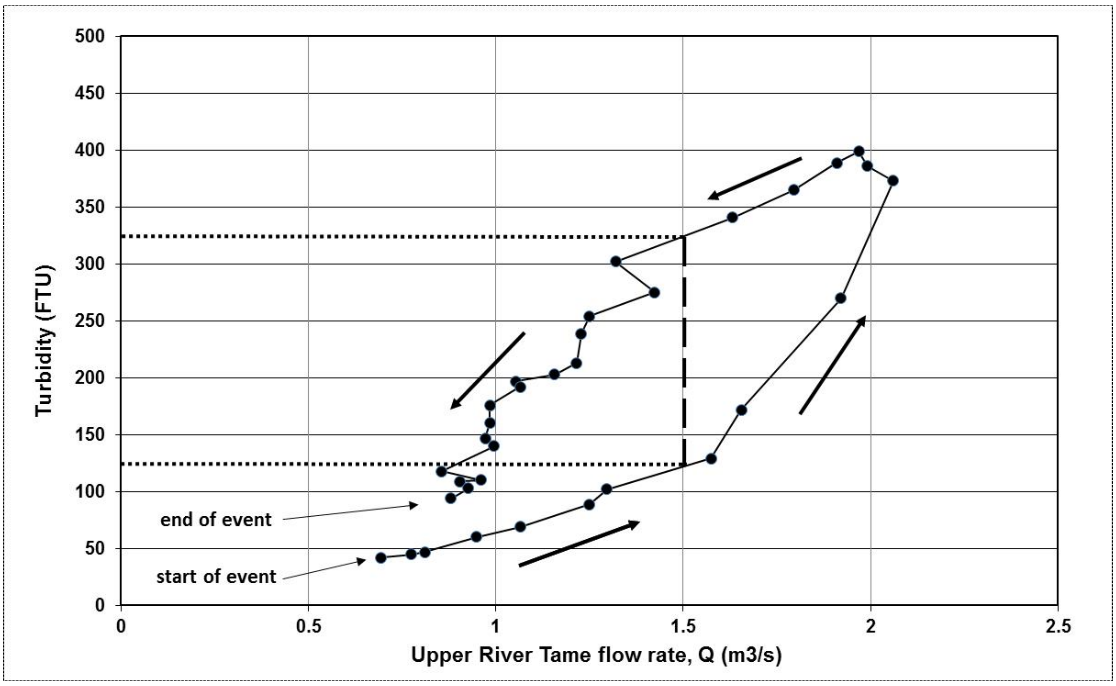

Figure 3. Clear anticlockwise turbidity hysteresis monitored at James Bridge gauging station, west Birmingham, for the storm event in Fig. 2 (14-15 March 2002). Automated observations were made at 15-minute intervals throughout the event.

It is clear from the example event in Figure 3 that the delay in the turbidity pulse results in strong *anticlockwise* hysteresis**.** Indeed, at an intermediate flow rate of 1.5 m^3 s^{-1}, for example, the turbidity value on the *recessional* limb is almost three times higher than the turbidity on the *rising* limb at the same discharge of 1.5 m^3 s^{-1}.

Preliminary work suggests that many other storm events analysed to date follow this pattern, with clear *anticlockwise* hysteresis (e.g. Lawler et al., 2006a).

Fig. 3 supports the idea that river flow rate (or any other flow index such as shear stress or stream power), is not necessarily a strong explanatory variable or a predictor of *fine* sediment transport in fluvial systems. Stronger relationships can generally be defined between *coarse* gravel transport and river flow variables.

6. DISCUSSION AND CONCLUSIONS

Typical turbidity responses in the Tame can be seen in Fig. 2 and 3. These show turbidity peaks clearly lagging discharge (Q) peaks. The resultant anti-clockwise hysteresis patterns here are contrary to First Flush Model assumptions, which predict hysteresis loops with a strong clockwise direction.

Work is ongoing to define the key variables which drive these anticlockwise hysteresis loops and late turbidity waves on the recessional limb of the hydrograph. Amongst others, key drivers are the roles of (a) Waste water discharges from Waste Water Treatment Works (WwTW) and (b) sewage which enters the River Tame from Combined Sewer Overflows (CSOs). These contaminants are likely to enter river systems during and after rainstorms, when Waste Water Treatment infrastructure is eventually overwhelmed during or after intense rainfall events. Indeed, Figure 2 shows a clear peak in Ammonia as the turbidity wave passes, and Ammonia is an indicator of sewage contamination of stream water here.

The First Flush model appears to have less application in the heavily urbanised Tame catchment, and further research is required to establish any additional multiple causes. Further work aims to develop analyses of longer-term records, and comparisons with downstream locations. It would be interesting to test, collaboratively, the First-Flush model in other urban or urbanising catchments worldwide, and this work would help to assess the generality of the findings here.

This result challenges the traditional First Flush Model. The FFM predicts that suspended sediment and/or turbidity peaks will occur *prior to* discharge peaks, before falling sharply. Much of the turbid water ingress appears to be derived from Waste Water Treatment Works or Combined Sewer Overflows (CSOs). These contributions are likely to be routed into the river at the end of a storm, when storages provided by holding tanks at sewage plants are breached.

This departure from the First Flush model requires further investigation to establish fully the controls, fluxes and processes in the River Tame - and if these are identifiable in other European and global world river systems. The next stage is to test for, and model, the controls on these anticlockwise turbidity and fine sediment transport dynamics.

Significant research gaps exist in the study of fine sediment fluxes and pollution dynamics in urbanised catchments more generally. Internationally, it would help to develop more general conclusions from compiling, modelling and interpreting worldwide hysteretic tendencies across many urban or rural catchments worldwide. One objective would be to assess the prevalence of negative hysteresis behaviour in urbanising river basins globally. An additional aim is to establish and compile a global inventory and database of fluvial fine sediment transport dynamics and patterns and datasets, including urban catchments: this will be called ‘SEDISTORE’.

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